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John A. Becker, R. O. Nelson

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Neutron-Induced Reactions and Spectroscopy with GEANIE

J. A. BECKER* and R. O. NELSON†

*Lawrence Livermore National Laboratory Livermore, CA 94550, USA
†LANSCE-3, Los Alamos National Laboratory Los Alamos, NM 87545, USA

Abstract. A large number of partial γ-ray cross sections produced in neutron-induced reactions with neutrons in the energy range $1 < E_n$ (MeV) < 200 have been measured over the past eight years. Partial γ-ray cross sections are measured as a function of incident neutron energy using the time-of-flight technique. Reaction channel cross sections were deduced from these measurements with the aid of nuclear modeling. Enabling facilities are the intense "white" source of neutrons at the LANSCE/WNR 60R 20-meter flight path, and the precision γ-ray spectrometry of the Compton-suppressed Ge detector array GEANIE. The first focus of the measurements was on the ^{239}Pu(n,2n) cross section, followed by a series of other experiments on nuclei throughout the periodic table, with an emphasis on neutron-fluence activation detectors (or "RadChem detectors"). Representative measurements will be presented, along with the techniques. Experiments in progress and future plans are mentioned.

INTRODUCTION

Neutron-induced reaction data for a wide variety of samples have been gathered taking advantage of the GEANIE (Germanium Array for Neutron-Induced Excitations) spectrometer sited at the Los Alamos Neutron Science Center's (LANSCE) WNR. Absolute partial γ-ray cross sections are measured for discrete γ-ray production caused by the interaction of energetic neutrons. The γ-rays are measured in GEANIE, a Compton-suppressed array of high-resolution ($\Delta E_\gamma/E_\gamma \sim 2/1000$) Ge detectors. The pulsed "white" neutron beam is produced by LANSCE/WNR, 800-MeV protons striking a tungsten target. GEANIE is located on the WNR 60 degree right (60R) flight path, and E_n for an event is determined with the time-of-flight technique. The flight path is ~20 m.

The goals of this now 8-year-old project focused at first on deduction of the *n,2n* cross section on the actinides samples ^{239}Pu and ^{235}U. The *n,2n* cross sections [1-3] were deduced from the measured γ-ray partial cross sections with an appeal to very careful and painstaking nuclear modeling using enhanced Hauser-Feshbach reaction codes. Inelastic scattering and the n,3n reaction were measured for ^{238}U at the same time [4]. The emphasis switched to samples of diagnostic "detector" nuclides following the actinide studies, with an emphasis on neutron-induced reactions on ^{89}Y, ^{90}Zr, ^{191}Ir, and ^{193}Ir [5-9], although many other samples were studied. Some studies have focused on nuclear structure [10-11] and others focused on neutron cross section standards – the contribution of Nelson, *et al.,* [12] to this conference. To date, 31 different samples have been studied at GEANIE.

A close collaboration between nuclear theorists and experimentalists marked the nearly decade long effort to address these issues from its inception, and continuing through the present time. Details of the enabling facilities can be found in [13,14]. The next sections describe a few features of the experimental arrangement, the irradiated samples, representative results, and potential efforts.

ENABLING FACILITY

GEANIE at LANSCE/WNR is a unique facility: A large Compton-suppressed Ge detector array sited on a 20-m neutron time-of-flight path with an intense energetic neutron flux, increased since 1996 by 3 × to ~10^4 neutrons/cm^2/s in a 1 MeV bin at E_n = 10 MeV. Characteristics of the neutron beam pulse structure are given in many places, including at this conference [8]. Features of GEANIE measurements include:

• Cross sections are measured as a function of E_n, for $1 < E_n$ (MeV) < 200, including the incident neutron region $9 < E_n$ (MeV) < 14, difficult for "mono-energetic" neutron production sources.

• The GEANIE array itself is evolved from the HERA array developed by Deleplanque, Diamond, and Stephens at LBNL. HERA was transferred from DOE/OS to DOE/DP in 1996. The array was augmented by 10 Planar Ge detectors at LANSCE to increase the capability for 100 - 800 keV γ-ray spectroscopy in a background of scattered neutrons.

• Time intervals up to the 8.3 ms between proton-beam macro pulses can be used to measure decay radiation, often providing in-place γ-ray efficiency calibrations using well-measured ß-decay radiation. Alternatively, lifetimes in this region can be measured.

The electronics and software of the data acquisition system are described elsewhere; the data transfer from CAMAC crate to computer is based on the MSU 4π System. All detector channels including the fission-chamber flux monitor are treated identically. This was a key concept of the data acquisition system, with the result that relative measurements are very accurate. The neutron flight path is well shielded, and the location on 60R provides a lower-background environment than on some of other WNR flight paths.

METHOD

Fig. 1 illustrates our method for extracting reaction channel cross sections. The example is for ^{239}Pu(n,2n) cross section. We measure energies and yields of discrete cascade γ-rays; the reaction channel is identified on the basis of known (characteristic) γ-ray energies. [Fig. 1(a)]. Yields are converted to partial γ-ray cross section [Fig. 1(b)] using calibrated detector efficiency, deadtime corrections, neutron flux, and target thickness. Fig. 1(c) illustrates schematically the conversion of $\sigma(\gamma_i)$ to σ(n,2n) with the aid of enhanced Hauser-Feshbach model calculations which predict the relationship between each $\sigma(\gamma_i)$ and σ(n,2n). In practice, an averaging was done, since the reaction model calculations are, in general, imprecise for the individual $\sigma(\gamma_i)$ [2]. The transformation depends less on the modeling input, the lower down in excitation energy the measurements are made [Fig. 1(c)]. For example, the $4_1^+ \rightarrow 2_1^+$ transition in the ground state band provides ~80% of the cross section at 10 MeV, and the model ~20%, while the $8_1^+ \rightarrow 6_1^+$ transition provides ~10% of the cross section directly with 90% owing to modeling. Fig. 2(a) shows the cross section for ^{239}Pu(n,2n).

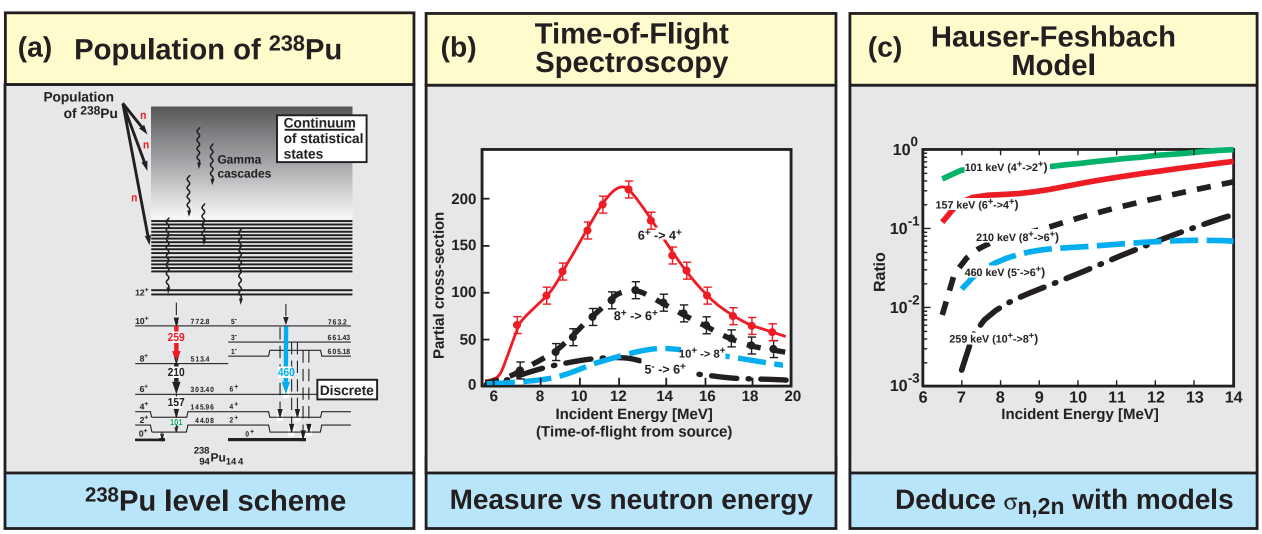

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FIG. 1. Schematic illustrations of ^{238}Pu population in the ^{239}Pu(n,2n) reaction (a), partial γ-ray cross sections $\sigma(\gamma_i)$ deduced from yields of discrete γ-rays at low excitation energy (b), and the transformation of $\sigma(\gamma_i)$ to σ(n,2n) using predications of enhanced Hauser-Feshbach reaction theory (c).

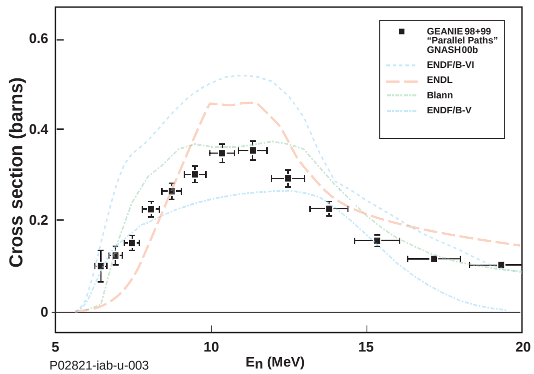

FIG. 2. The $^{239}Pu(n,2n)^{238}Pu$ cross section deduced from the GEANIE measurements [1,2] compared with prior evaluations.

Mixed Sample Technique

The precision energy determination and line shape characteristics of the Compton-suppressed Ge detectors allow the use of mixed samples and simultaneous measurement of cross sections for different nuclides, since the γ-rays can be related to the corresponding sample. We began the practice of including natural iron foils (typically on each side of the sample), measuring the yield of the ^{56}Fe $(2_1^+ \rightarrow 0_1^+)$ transition, a standard cross section [15]. This procedure gives confidence in the experimental arrangement and data reduction (and if required a normalization). The Fe cross section values have been more accurately determined in our work. We find the Simakov value to be high by about 10% to 705 mb at E_n = 14 MeV, following Nelson *et al*. [12].

ILLUSTRATIVE RESULTS

Cross section results for some RadChem detectors are presented next: Fig. 3 illustrates the results [9] for $^{193}Ir(n,n')^{193m}Ir$, i.e., population of the ^{193}Ir isomer with E_x = 80 keV by inelastic neutron scattering. Results of the GEANIE team are compared with the earlier activation results of Bayhurst, et al., [16] and the 1998 ENDF Evaluation. The use of the "white" source coupled with the time-of-flight technique to expose the shape of the cross section as a function of incident neutron energy (E_n) is nicely illustrated in Fig. 3.

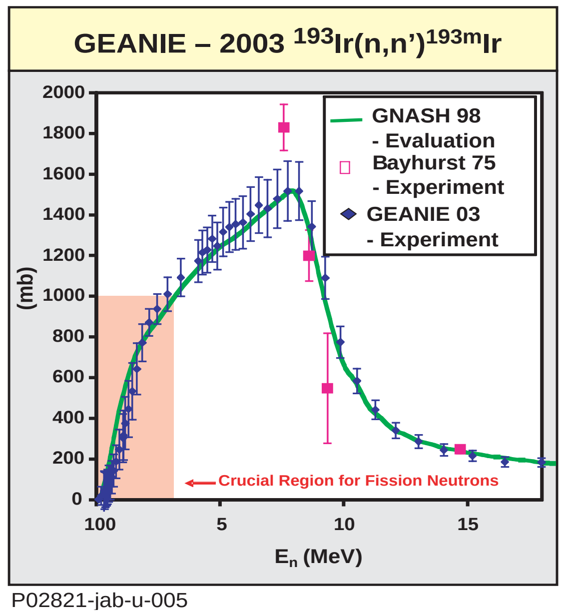

FIG. 3. The cross section for production of the Ir-193 isomer (^{193m}Ir) at E_x = 80 keV [9].

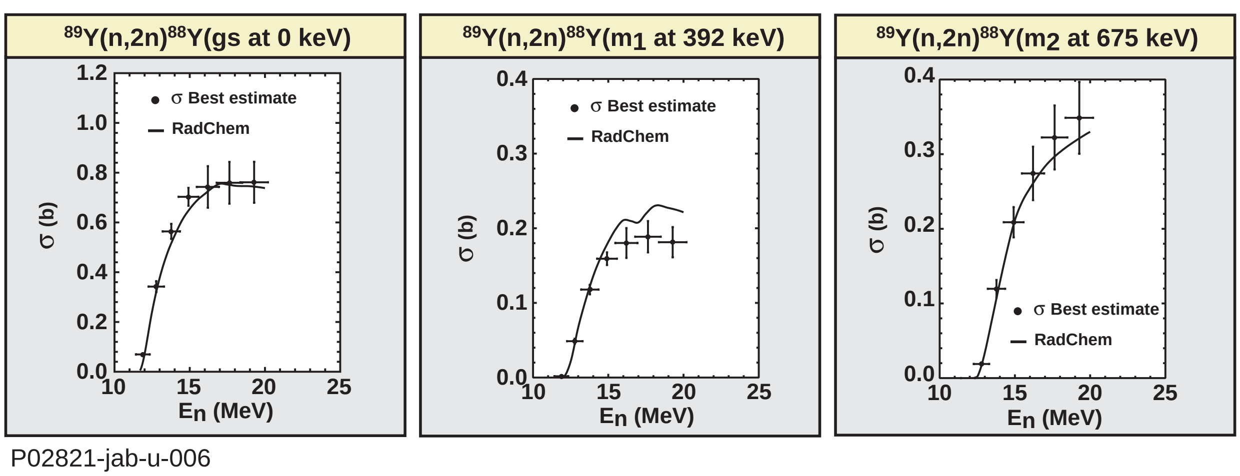

FIG. 4. The $^{89}Y(n,2n)$ cross section decomposed into 3 components corresponding to production of ^{88}Y in its ground state, "m1" isomer at 392 keV, and "m2" isomer at 675 keV. [5,6].

Fig. 4 illustrates the advantage of the GEANIE experimental arrangement to deduce ground state and isomer cross sections [5,6]. ^{235}U fission has been studied both through γ-ray measurements with "thick" samples [17] and through x-rays using "thin" ^{235,238}U deposits on solar-cell fission detectors [18-19]. Fig 5 shows (preliminary) results [10] for a rotational band in ^{197}Au based on the 11/2$^-$ isomer in ^{197}Au. We close this section with 2 cross section examples obtained with ^{150}Sm and ^{75}As samples.

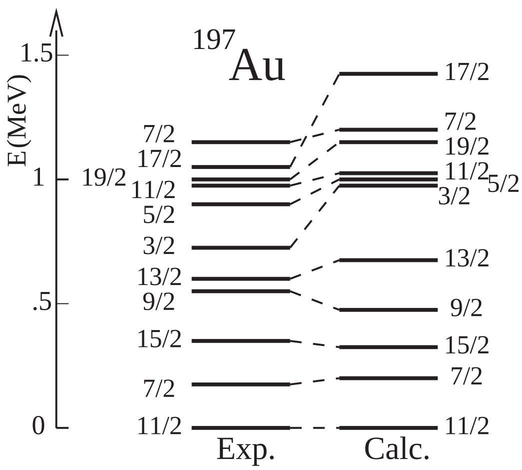

Fig. 5. Newly-established ^{197}Au π = "-" states above the 11/2$^-$ isomer compared with preliminary particle-plus-triaxial-rotor model calculations (β=0.13 and γ=45°) done by K. Starosta (Private communication, 2004).

Fig. 6 illustrates the ^{150}Sm(n,2n)^{149}Sm cross section [20], and Fig. 7 shows the measured cross section for isomer production in the ^{75}As(n,2n) reaction [21].

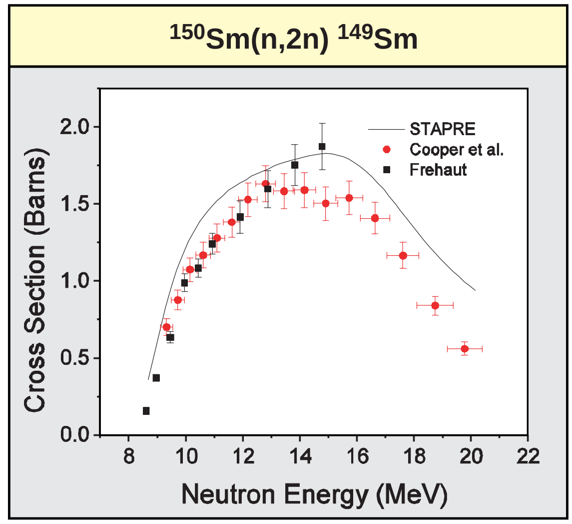

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FIG. 6. The ^{150}Sm(n,2n) cross section [20] compared to the measurements of Frehaut, *et al*. [22] and the prediction made with the STAPRE code [23].

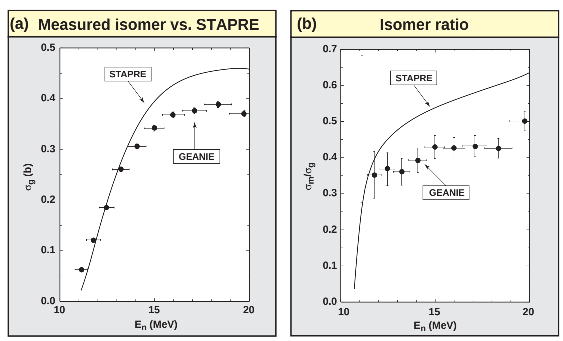

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FIG. 7. Production of the ^{74}As isomer at 259 keV via the ^{75}As(n,2n) reaction.

FUTURE ACTIVITIES

^{48}Ti + n reaction study

A study of ^{48}Ti + n is being completed as a Ph.D. thesis for Dugersuren Dashdorj [24] (G.E. Mitchell, North Carolina State University, Major Professor). ^{48}Ti is one of the lighter nuclei we have studied at GEANIE. Reaction model cross-section predictions for the several open light particle-emission channels are being compared with measurements (See Fig. 8).

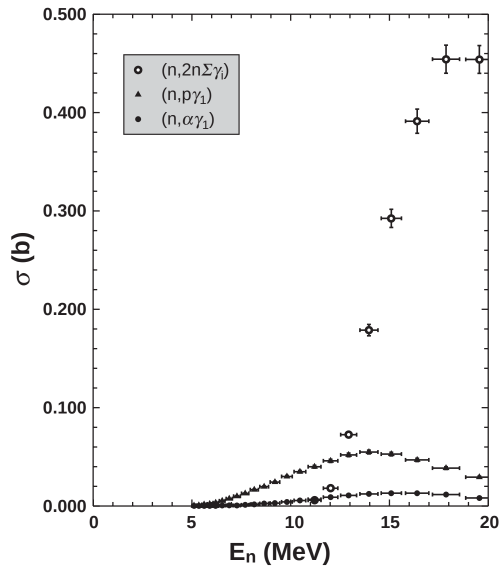

Fig. 8. Unpublished preliminary results for several outgoing channels for n + ^{48}Ti reactions [24].

Preequilibrium

The preequilibrium reaction mechanism is the usual explanation invoked to explain the high energy neutrons (as opposed to boil-off neutrons) which are emitted as the incident neutron energy increases above B_n. The residual nucleus is left at lower excitation energy where the level density is low, and low-spin states are generally dominant. Most of the evidence for preequilibrium comes from fast neutron spectroscopy. The data in Fig. 9 suggest evidence in the γ-ray channel for preequilibrium particle emission. Fig. 9 (a) and (b) compare the population of the ^{90}Zr 2_1^+ state and the 6_1^+ state, divided by the inelastic channel cross section [7]. As the neutron energy increases beyond 15 MeV, the ratio for the 2_1^+ state increases, and the corresponding ratio for the 6_1^+ state decreases. We plan further exploration of preequilibrium in bombardments of ^{186}W and of ^{170}Er, where shell structure plays less of a role in data interpretation than in ^{90}Zr.

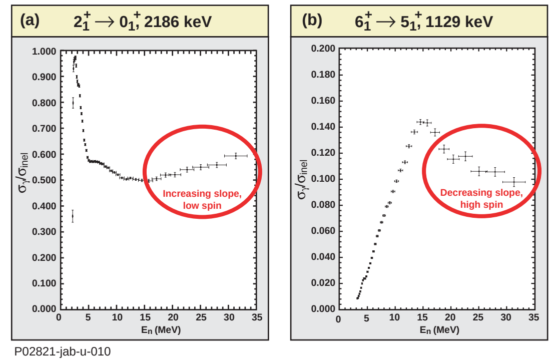

FIG. 9. Cross section ratios for ^{90}Zr(n,n′). σ(2_1^+) / σ(n,n′) (a), and σ(6_1^+) / σ(n,n′) in (b). Data from Ref. [7].

Isomer studies and searches

We have the capability to measure properties of isomeric states with lifetimes in the range, ~ 1 μs < $\tau_{1/2}$ < 10 ms. The result of a lifetime measurement [25] for the 797-keV transition in the $K^\pi = 19/2^+$ decay chain in ^{175}Lu is shown in Fig. 10. Time is measured relative to the end of the LANSCE proton accelerator macro pulse.

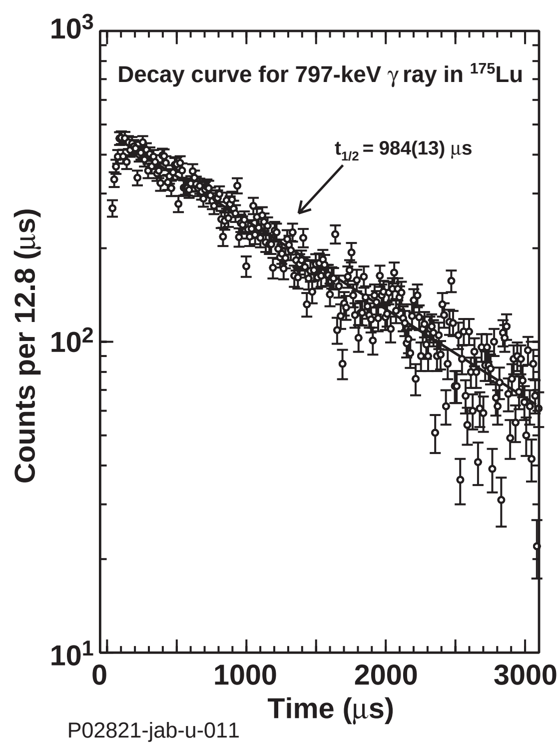

FIG. 10. Decay curve for the 797 keV γ-ray in ^{175}Lu [25].

GEANIE IMPROVED

An array of 4-6 suppressed “clover” Ge detectors coupled with the present GEANIE planar detectors offers significantly more efficiency than the present GEANIE array. The coaxial detectors of GEANIE are approaching 20 years of service; they are typically 20-25% efficient (compared to a 3″ × 3″ right cylindrical NaI(Tl) detector for $E_\gamma = 1.33$ MeV). An array of “clover” detectors (4 or more), with suppression shields offers the same or more efficiency for 500-keV γ-rays, and significantly increased efficiency for 1.5 MeV and higher-energy γ-rays. This “improved” GEANIE makes significantly more efficient use of beam time.

CONCLUSION

The combination of a powerful Compton-suppressed Ge detector array and the pulsed intense neutron source at LANSCE/WNR provides new nuclear data, and gives experimentalists the opportunity to gain information on the pre-equilibrium reaction mechanism, with the result of improved models of nuclear reactions – important physics. With an upgraded GEANIE, the measured physical data will be improved due to the greater detection efficiency for > 1 MeV γ-rays – important for example in the spectroscopy of both actinide and for nuclei near A = 50 and 90 where shell effects are important and MeV γ-ray energies are typical of vibrational decay.

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